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"REQUIREMENTS, DESIGN FEATURES AND MANUFACTURING TECHNIQUES LEADING TO REDUCED OPERATIONAL COST FOR ADVANCED MILITARY AIRFRAME STRUCTURES"

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0 Introduction

Reliability has a key role to play in successful deployment of the Eurofighter/Typhoon, because its air force customers are relying on improved availability rates, and therefore buying fewer aircraft than would previously have been required.
A set of M, R + T-requirements derived from previous in-service-aircraft-programmes has been established, amended by new technology potentials and airforce customers demands.
Selected design criteria, design features and manufacturing techniques supporting the goal of reduced operational cost are detailed below.

1 Requirements affecting operational cost

Life Cycle Costs (LCC)
Life Cycle Cost assessment plays a increasing role in the acquisition of aircraft both for military and commercial operators.
Military and commercial customers emphasise the need to optimise cost and benefit ratios from the feasibility phase up to the in service phase.
An extrapolation of Life Cycle Cost of existing aircraft over a 30 years in-service period shows an impact of Logistic Support Costs of about 60 %.
(see fig 1.1) Extrapolation of LCC

Consequently a main aspect of the Life Cycle Cost optimisation process is the reduction of Costs for Logistic Support. This fact is reflected in an appropriate product support concept which is based on qualitative and quantitative requirements.

RM&T requirements
The consideration of following qualitative requirements has a substantial influence on the aircraft downtime, the necessary maintenance effort, the number and complexity of required Ground Support Equipment and the amount of spare parts.
Reliability requirements:
- Safe Life Design
- Fail Safe Design / Damage Tolerance
- Optimisation of defect rate by
    - Corrosion prevention / protection
    - Selection of adequate materials
    - Analysis and assessment of stress profiles

Maintainability Requirements:
- Accessability (on and off aircraft), (structure + equipment)
- Ergonomic aspects
- Repairability
- Modularity
- Standardisation
- Interchangeability
- Replaceability
- Simplicity of design

Testability Requirements:
- Structural Health Monitoring (service life vs. design life)
- Onboard data processing capability
- Parameter exceedance monitoring capability

The realisation of those requirements by application of logistic support methods from the beginning of the concept

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phase leads to significant reduction of logistic support costs.

The quantification of specified requirements in comparison to logistic parameters of existing aircraft provides target features to be met.
(see fig. 1.2)

Quantification is performed using mathematic models and comparable data of aircraft already in service. Allocation of different aircraft parameters (e.g. defect rates, maintenance man hours / flying hour etc.) are a measurement for the reliability and maintainability features of an aircraft and their impact on the Life Cycle Costs. Those figures show the expected aircraft parameters in an early stage of the aircraft development phases.
(see fig. 1.3) M-Allocation

2 Design Principles and Criteria

As already mentioned above the operational cost of an A/C play a significant role especially in the environment of restricted military budgets.
By the time the design of a combat aircraft is frozen a large percentage (about 80 %) of the life-cycle costs have been predetermined. Therefore, to meet the challenge of low in-service costs, consideration to the above must be given at an early stage in the design phase.
Product support considerations are already included in the structural design criteria and are covered by the applied design principles.
Developing and designing a high performance aircraft itself is a complex process with inputs and requirements from many disciplines. In opposition to this, the operational cost considerations are providing conflicting requirements. The final product is a compromise between all inputs and aspects from technical and support disciplines.
Life-cycle costs are directly related to fatigue and damage tolerance calculations. In addition to these also the accurate definition, establishment and simulation of design loads within the flight envelope, the consideration of aeroelastic effects and in general the accuracy of the analysis methods that are used influence the operational cost of a combat A/C.

2.1 Damage Tolerance (Composite Structure)

The general damage tolerance requirements are considered in the A/C design by adopting the following measures:

- Structural redundancy
- Selection of materials and methods of design with low sensitivity towards external effects and with good resistance to damage growth
- Design methods assuring that details are not prone to damage by impact, environment or abnormalities in manufacture

In addition, the specified Bird Strike capability has to be guaranteed.
Since a large extent of the outer surface is designed and built from CFC material, it is necessary that impact damage is considered in the design of these structural items.
The primary problem of composite structures is that a damage caused by a low velocity impact may not be visible. This means a delamination caused by the impact cannot be seen with naked eye but needs detection by NDT.
Visible damage on a monolithic structure will generally be repaired and the strength of the structural part will be restored.
Non-visible damages will remain in the aircraft structure and it has to be ensured that these damages never lead to failure of the structure within the service life of the A/C.
The visibility threshold for composites may lie around 0.2 mm indentation depth but nevertheless depends on the surface properties. Generally it is not deemed suitable to base a damage tolerance criterion for monolithic structures on the visibility of impact damages. A better approach therefore is to identify the potential impact risks within individual zones of the structure and then design the airframe accordingly.
For sandwich structures with their typical thin skins however, a low energy impact, e.g. 8 J, may already produce indentations of about 1mm depth that are well visible.
The possible impact energies have to be established by assessing risks resulting from normal routine, everyday servicing of the A/C and normal operating threats. *Table 2.1* presents the established impact energies based on an assessemten as mentioned above.

In order to cover the effects of these occurrences, damage tolerance design allowables have to be established accordingly. They are considerably lower than the laminate strength and are based on compression

after impact test results. The compression after impact allowable depend on both the impact energy and the laminate thickness.
For tension strength, the reparability requirement already covers the damage tolerance requirement.
The damage tolerance allowables are used to design the structure. The qualification of the structure and the validation of the damage tolerant design is performed by static and fatigue testing.
This is done by incorporating representative impact damages in structural test components. A schematic "Route to Impact Resistance Verification" is shown in Chapt. 5.1

2.2 Fatigue Design (Metal Structure)

The fatigue behaviour of an A/C during the whole in-service life is influencing the operational costs to a large degree. A good fatigue design covering all the different requirements and considering the operational usage, as specified in the contract, of an A/C is therefore very important.
The requirements regarding fatigue are established in the Durability Criteria which form an important part of the Weapon System Specification.
The important requirements are specified as *Flight Hours, Number of Landings, Service Life and Mission Profiles*.
In case of Eurofighter/Typhoon a "Safe Life " Design is required .
In order to meet this requirement safe fatigue endurance curves (SN-curves) have been used by applying a scatter factor of 3 on life at the low endurance/high amplitude region of the SN-curve and a factor of 1.4 on strength at the high endurance/low amplitude region of the SN-curve .
Very early in the design process, fatigue allowable stresses based on the specified life/spectra for different metallic structural features (stress concentration factors and materials) have been generated.
Detailed fatigue calculations are performed to recognise and understand at an early stage the possible problematic areas and to guarantee the endurance of the A/C. At fatigue critical areas detailed FEM investigations are performed to identify local load paths and stress concentrations.
The fatigue life analysis is supported by fatigue testing of structural items.
All identified problems and damages are leading directly to a redesign of the affected structural part.
The validation of the fatigue design is based on the fatigue analysis and on the result of the extensive fatigue test programme. The final fatigue strength qualification is demonstrated by a full scale fatigue test (MAFT) and associated major fatigue tests. It has to be demonstrated that the full static strength (100 % D.U.L.) can be achieved after testing for twice the required aircraft life additionally the structure must sustain 80 % D.U.L. after completion of the fatigue test of 3 aircraft lives.
The fatigue verification including a schematic "Route to Fatigue Verification" is treated under Chapt. 5.2.

Operational costs can also be reduced by fulfilling the Inspection-free Concept which requires:

- The structure during its operational life shall not develop cracks or damages requiring attention under the design loading spectrum and environmental conditions so that no specific scheduled preventive structural inspections for fatigue are necessary
- Scheduled structural inspections for purposes other than fatigue shall be by visual inspection only. It is a design aim that all parts of the structure shall be accessible for inspection and rectification
- New methods of construction shall not cause the need for extra scheduled inspections or contravene the safe life philosophy.

In order to fulfil the Inspection-free Concept of the structure the described procedure has to be applied by considering fatigue aspects from the beginning of the design phase of a new A/C.

2.3 Structural Health Monitoring System (SHMS)

Based on the Safe Life concept the occurrence of fatigue cracks within the specified A/C life is considered to be improbable. This concept undoubtedly yields reasonable overall results however incidental fatigue damages including cracks continues to occur.
One main cause for such unexpected fatigue problems is considered to be the difference between in-service load spectra and specified design assumptions over an usage life of 25 —35 years with increasing tendency for modern A/C.
Therefore Eurofighter/Typhoon will be equipped with a Structural Health Monitoring System (SHMS).

The SHMS performs real time fatigue calculations based on flight parameters and/or strain gauge responses and determines the life consumed by the airframe. Significant structural events and flight performance parameters (auxiliary data) are also monitored. Comparisons between fatigue design assumptions and in-service load spectra will be performed in the Ground Support System (GSS) on squadron level for each A/C. In addition the GSS supports engineering staff in the maintenance of the A/C.

2.4 Corrosion Prevention Plan

A permanently improved Corrosion Prevention Plan evolved from previous civil and military programmes has been applied for:

- material selection / combination
- design rules
- protective measures

Attention has been paid to the combination of aluminium alloys and composite structures.

3 Design features

Design features contributing to a significant reduction of operational costs are described below.

3.1 Maintainability / Accessibility on Aircraft/off Aircraft

Reliability. maintainability and testability were given the same priority as aircraft performance and cost.

Product support considerations have influenced the design of the Eurofighter Typoon from the beginning. Accessibility is the key feature to achieve excellent maintainability together with sufficient clearance for the standard hand tools.

The general structural concept takes into account, that the equipment bays are positioned in eye / chest level working height.

(see Fig. 3.1)

M, R + T consideration have been influenced permanently by the International Air Force Field Team. M, R + T improvements or non-compliances have been described in a maintainability observation sheets prior to their design incorporation.

3.2 Repairability of Aircraft

An analysis of in-service A/C-structures at DASA indicated following major damage modes:

- Corrosion
- Fasteners / latches (wear, locking device)
- Fatigue

The aircraft structure is designed using standard metal materials or composites materials to ensure availability along the whole life cycle.

For repairability high loaded structure prone to be damaged is designed in the following way:

- edge distance for connecting bolts is increased 2 times bolt diameter plus 1 mm
- machined parts which have reinforcements in web areas are designed with extra lands for repair solutions.

The aim is to design structures leading to reduced repair costs and consequently to reduced downtime.

3.3 Modular major components

The airframe structure consists of 6 major components:

- Forward fuselage	- Foreplane
- Centre fuselage	- Wing
- Rear fuselage	- Fin

These major components are designed to be completely equipped prior to final assembly operation. In addition most of the systems are already tested in the major component stage i.e. landing gear, fuel tank leakage tests, ...). This is to detect defects already in the major component stage of assembly. In case of severe damages replacement of major components with systems equipped is therefore possible.

3.4 Interchangeability and replaceability

Access panels and structural components exposed to potential damage are to be fully interchangeable (ICY) i. e. no trimming, drilling etc. is acceptable. A dedicated design as well as modern manufacturing techniques allowed a significantly higher percentage of fully interchangeable components.

The effects on operational cost are:

- Less spares required
- Reduced A/C-down time

3.5 Robust design solutions

- Extra landings in selected applications

- Anti wear provisions (bushings)
- No bonded joints for primary load pathes
- Conservative bolted joints
- Minimum bolt diameter 8 mm on removable panels
- Edge protections on composite structure for erosion

3.6 Integral fuel tanks

Integral fuel tanks, particularly in the fuselage, require extra attention in view of reliability of the sealing method, their testability and repair.

At least one barrier in the most critical areas can be resealed by reinjecting sealant-material.

(see fig. 3.6) Integral fuel tank sealing

3.7 Selection of material, semi-products and standard parts

For airframe structure only certified materials are used. The manufacturing processes are qualified and are of state of the art.

Advanced materials and processes are only used if the technology is qualified and risk is minimised.

The materials used in airframe structure are reduced to the minimum of types. Standard parts e. g. fasteners, latches and quick release fasteners are also reduced to a minimum of different types to improve supportability

Materials banned by the Montreal-Protocol are avoided. This is to reduce precaution efforts regarding health safety standards during the whole life cycle.

3.8 Digital Product Assembly

(see fig. 3.8)

With the start of designing the Eurofighter/Typhoon production aircraft, the participating companies decided to introduce the so called DPA (Digital Product Assembly) process.

DPA is the process/methodology which embodies the use of common CAD tools, common standards and procedures.

DPA ensures the simultaneous and controlled access to all engineering data both within the industry and the customers.

The inclusion of a „Product Data Manager" (PDM and the model technology provides the control mechanism needed to operate in a virtual A/C representation)

(DMU = Digital Mock Up)

The main features of the DPA process are as follows:

- Part based design
- Solid modelling
- Company functions integrated
- Robust product configuration management
- Complete, nearly on line, visibility of the whole product to each user including the customers.

The selection of the tools plays an important role in order to work in a DPA environment.

3.8.1 Design Tools

The 4 participating companies have commonly decided to use

- CATIA for all geometric design tasks
- Mentor Graphics L-Cable for the electric design
- E3D for loom installation package

The selection of VPM (Virtual Product Model) as a local data manager with CATIA and 4D Navigator acts as an integrated system to provide to the customer a complete virtual training environment.

3.8.2 Product Data Manager (PDM)

Pending on the internal requirements each company have selected a PDM tool which fits their internal business.

However the main requirement for use in a DPA environment it has been ensured that the different PDM's have the following essential features for the necessary data exchange:

- Compatible capability in each tool
- STEP compatible
  - STEP tool will enable PDM's linked together electronically
- Common data model
  - Data requirements and formats
- Common integrated processes.

3.8.3 Implications

The process enables:

- On line near real time access to the weapon system data for all in service aircraft and pending deliverables.
- On line design support for repair incl. in service repair
- A configuration control system for each aircraft and networked between all operator locations and industry.
- Virtual training environment for ground crew

and aircrew.

- Step towards interactive technical manuals.
- Knowledge based fault diagnostic tools.
- Early identifications of spares for repairs.

This leads to the following benefits:

- Evolution from reactive support to proactive support.
- Significant increase in the final product quality.
- Common data
- Direct on line access to customer
- Improved customer support
- Reduced „Life Cycle Costs"

The DPA process is regarded as customer service orientated with the target of better response times and enhanced technical quality resulting in a higher aircraft availability.

4 Manufacturing Techniques

4.1 Manufacturing Techniques

The aim for affordable technology for improved products require an integrated approach of Engineering and Product Process Definition. The implementation of an integrated Quality Assurance Process, such as automated process control, on-line Non Destructive Testing, provides low-cost components at high quality. Available manufacturing techniques are showing significant improvements in terms of:

- Tolerances: Bolt pattern of mating interchangeable components can be NC-drilled separately
- Repeatability of processes
- Tolerances of steps and gaps
- Detectability of inherent failures/tolerances.

(see fig. 4.1) Foto YOMACH

4.2 Concurrent Engineering and Virtual Manufacturing Simulation

Emphasis in design has turned to concurrent engineering, design for maintainability, accessibility, and virtual manufacturing, producing verified manufacturable data based on the designed geometry.

4.3 Castings / Forgings

Castings provide great contribution to cost reduction since stereo-lithography became available consequently modular components can be provided in reduced lead time.

5 Qualification / Certification

The efficiency of the provisions incorporated in the design of the A/C structure to improve maintainability and to guarantee the required interchangeability of structural parts has to be demonstrated to the customer on a number of production A/C.

The qualification and verification of the "analytical" measures and methods applied to take care about the operational costs are part of the general qualification and verification process of the structure and is shown in Chapt. 5.1 and 5.2 respectively.

5.1 Damage Tolerance Verification

The shown flow chart gives an overview about the route to impact resistance verification or in other words the route to validate and qualify the applied damage tolerant design of the CFC structure.

(see fig. 5.1)

The applied process guaranties that the damage tolerance allowables used to design the structure, the development experience as well as the test results of the real CFC structure is considered and used in the design phase of the structural parts.

The verification is based on analytical and on qualification test results.

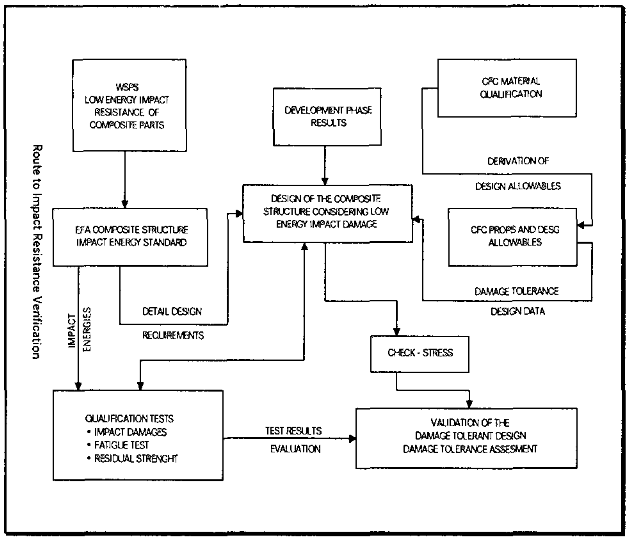
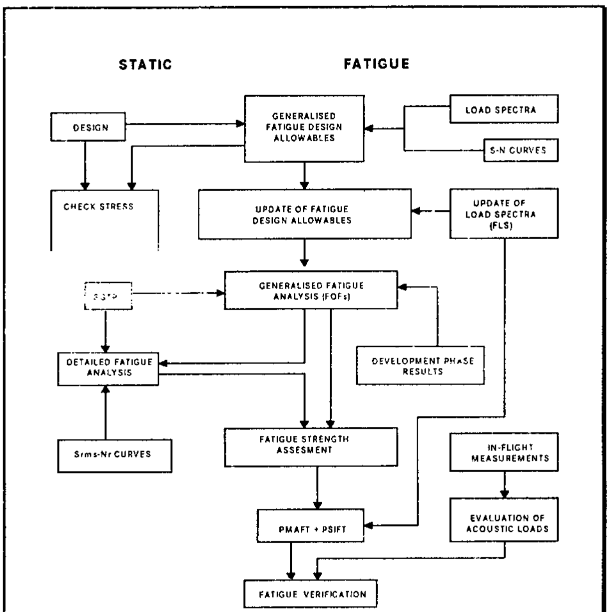


fig. 5.1

5.2 Fatigue Verification

The in *fig. 5.2* presented flow chart gives an overview about the route to fatigue verification of the airframe. It is also guaranteed that in the early phase of the design process the fatigue allowables are available and are applied and that during the design phase the development experience, results from structural ground test programme (SGTP) as well as loads updates are considered.

The verification is based on the fatigue analysis supported by structural testing . The final qualification is performed by fatigue testing of a production standard airframe.



Route to Fatigue Verification

fig. 5.2

5.3 Interchangeability demonstration

For certification, interchangeability has to be demonstrated to the customer to verify full interchangeability between different aircraft after a defined minimum of flight hours. This is to ensure that flights in defined envelopes and normal wear will not result in structural deviations leading to a loss of interchangeability.

6 Summary

The impact upon life cycle cost become much more important and is affected by

- decreasing budgets available
- increasing energy cost expected
- increasing time between aircraft renewals

As a consequence any future product has to aim for:

- Nearly maintenance-free components
- Less expensive methods of inspection, preferably avoiding expensive tear-down
- Reduced repair costs as repair and replacement of components become more important affecting the requirements for replaceability and interchangeability
- Reduced down-time

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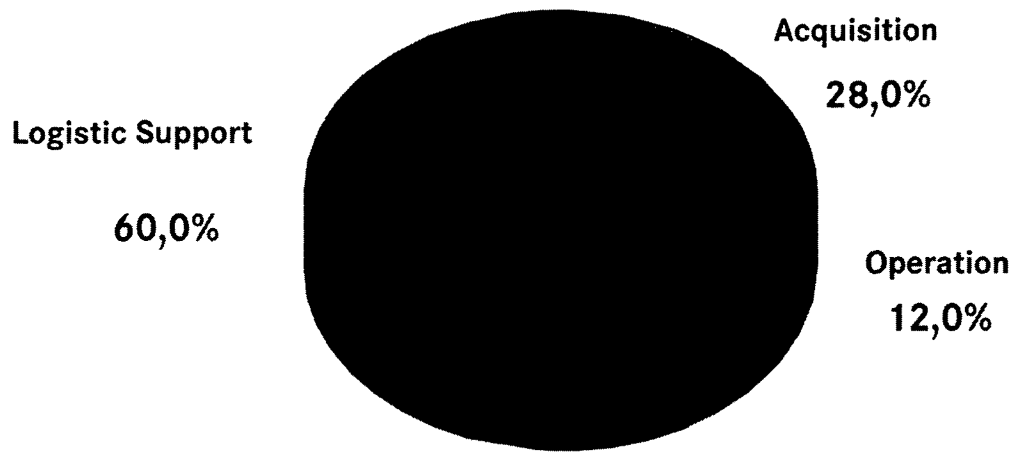

Fig. 1.1: Extrapolation of the Life Cycle Costs
(ass. 30 Years In-Service)

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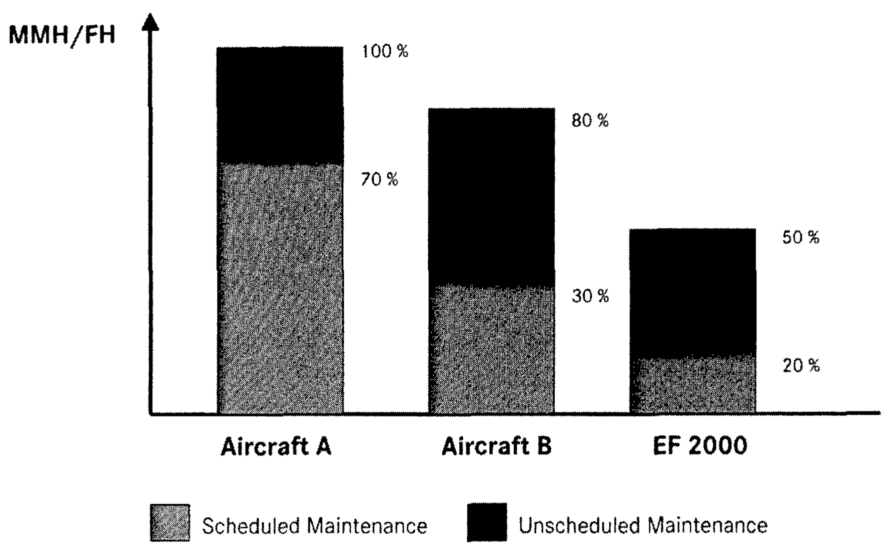

Fig. 1.2: Maintenance Effort

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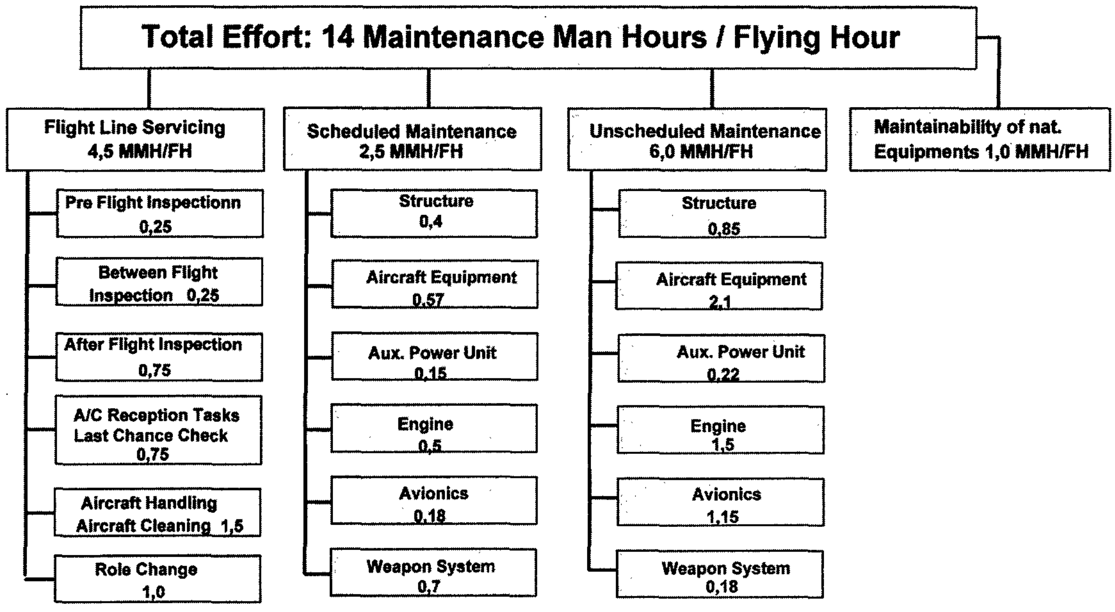

Fig. 1.3: M - Allocation

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SECTION	ZONE	ENERGY (JOULE)	IMPACT INCIDENTS COVERED
F/F	Sill	8	Normal servicing, Hail
	Bottom	8	Normal servicing
	Foreplane spigot region	20	Normal servicing, Installation
	Montage of Canopy region	20	Normal servicing, Hail
	Side skin	8	Normal servicing
	Radome	8	Normal servicing, Hail
C/F	CFC Skin Top	8	Hail
	CFC Skin remaining	20	Normal servicing
	Bottom panels	8	12,7 mm Dia Runwaystone
UPPER WING surface	Apex Region	8	Normal servicing, Falling tools, Hail
	Wing-Fuse Fairing	8	
	Skin (between Fairing and Y2100)	30	
	Flaperon (between Fairing and Y2100)	8	
	Skin (outboard of Y2100)	8	
	Flaperon (outboard of Y2100)	8	
LOWER WING surface	Apex Region	8	Normal servicing
	Wing Fuse Fairing	8	Runwaystone
	Main Wing Skin	17	Runwaystone
	Flaperon	8	Runwaystone
R/F	Top	8	Hail, Falling tools
FIN/RUDDER	Fin	20	Normal servicing
	Rudder	8	
	Precooler	8	
A/C	Internal Stucture	8 (minimum)	

Table 2.1: Potential Impact Damage Assessment

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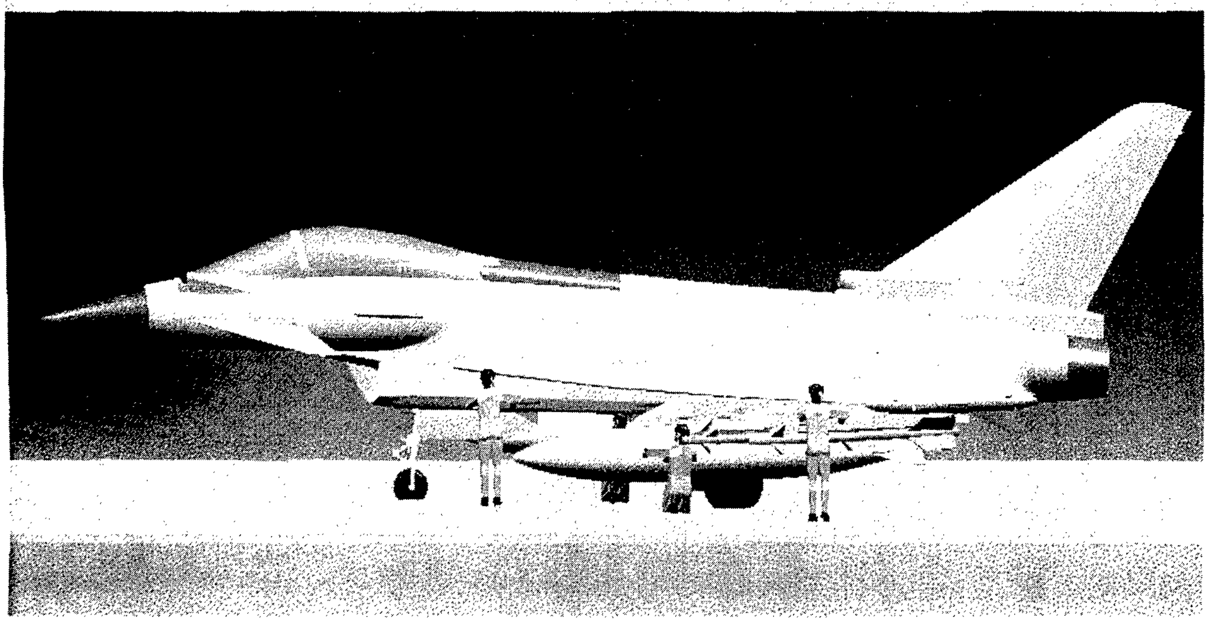

Fig. 3.1: EF-Typhoon Maintenance

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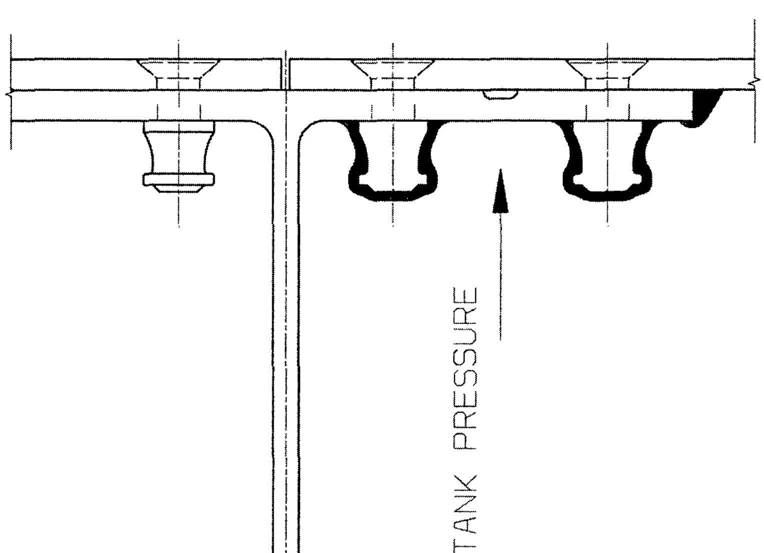

Fig. 3.6: Integral fuel tank sealing

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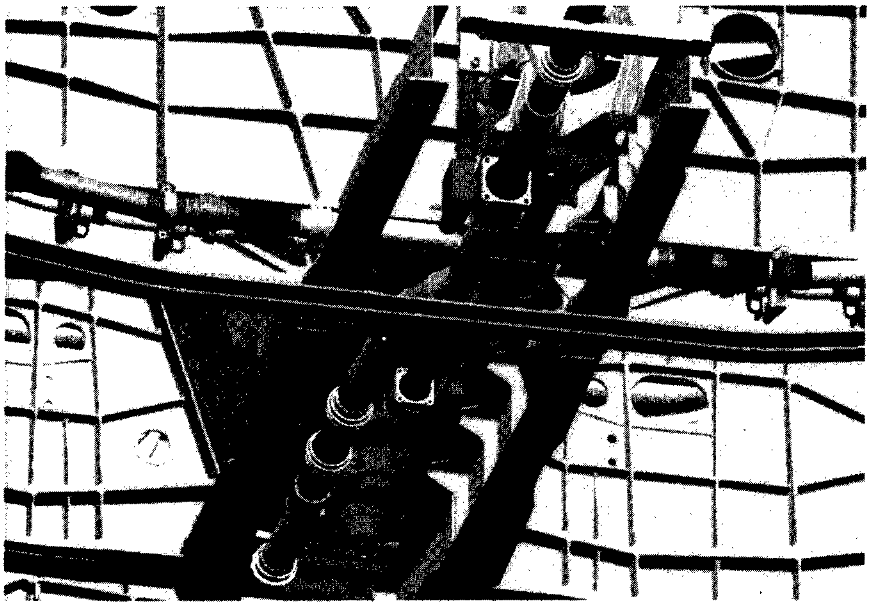

Fig. 3.8: Digital Product Assembly

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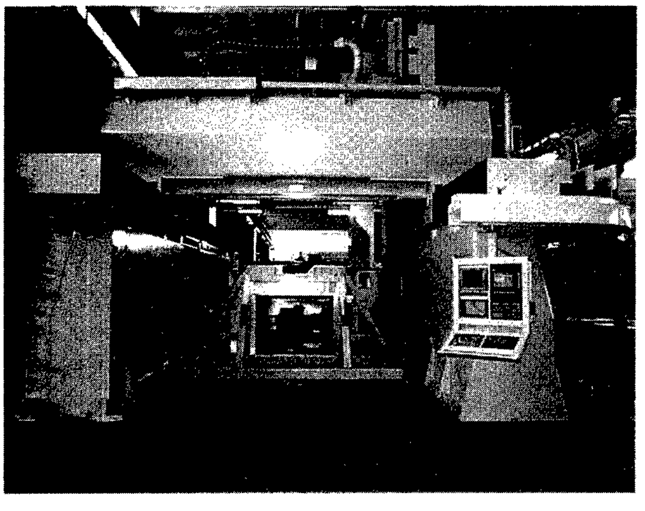

Technical Data:

X - axis 8300 mm
Y - axis 3200 mm
Z - axis 2000 mm
A - axis 200°
C - axis 400°
Spindle Capacity: 17 kW
Spindle Rotation: 9 000 rpm
Feed: 16 000 mm/min
Tool Capacity: 40 places

Application:

- Drilling of CFC-skin to CF structure
- milling interfaces to front and rear fuselage
- Drilling of ICY and non ICY substructure for Doors and Panels
- Drilling of Centre Fuselage Spine hole pattern

Fig. 4.1: Assembly Centre Fuselage